ON THE FEASIBILITY OF INDUCING CAVITATION IN HAILSTONES AND SUPERCOOLED WATER BY LOW INTENSITY SHOCK WAVE

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ABSTRACT. Preliminary experimental results to elucidate the mechanism of the induction of cavitation in supercooled water and ice by means of ultrasonic waves are presented here. Neither the induction of cavitation nor the weakening of ice could be affected by means of ultrasonic waves having the intensity of 16w/cm^2 interacting for 2 minutes. A value of 72 atmosphere has been obtained as the tensile strength of degassed distilled water at 3·5°C under shielded condition. Further no appreciable weakening could be detected in hailstones and ice blocks after exposure to explosion. Attempts have been made to explain these results in terms of the existing theories of cavitation.

INTRODUCTION

The question raised here is whether elastic waves in the form of shock waves generated by lightning discharges, jet plane flights, explosions, rupture of diaphragms in laboratory experiments, can induce cavitation in supercooled water droplets and hailstones. The author describes here his preliminry findings to elucidate the mechanisms of the induction of cavitation in supercooled water and ice by means of ultrasonic waves.

Recently much attention has been drawn to the possibility of softening hailstones by blast waves due to explosion. Vittori (1960) has shown the possibility of breaking up watery hailstones by blast waves. He interprets his observations on the theoretical assumption of the formation of acoustic waves induced cavitation in the water component of the hailstones. He has not given any proof, however, to show that hard dry hailstones could partly be liquified and then broken. Further, the theoretical calculations are made assuming water at room temperature (25°C), but the water component in hilstone is at 0° or less. The physical properties of water at 0°C or less differ greatly from those at 25°C.

Viscosity of liquid plays a very important role in determining the threshold energy for forming a bubble of critical size. The viscosity of water at 0°C is almost

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double that at about 25°C. At lower temperature, the threshold energy for cavitation will be higher. Therefore, it is essential to introduce the necessary corrections for the parameters responsible for the formation of cavities. Vittori (1960) did not include those corrections in his calculations. Under this situation, the application of the cavitation theory seems to be in some doubt. Vittori results were challenged by Roncali (1960a) and List (1963) on the basis of their experimental evidence. List concludes from the results of a series of experiments that no effect is produced by blast waves from charges of up to 1 kg TNT on the mechanical cohesion of ice objects at a distance of 5 meters.

Liquid to solid phase transformation of suprcooled water by physical methods such as shock wave, ultrasonic waves and mechanical agitation, has attracted the interest of many workers. Laboratory experiments demonstrate clearly that elastic waves can trigger freezing of supercooled water. But the recent efforts are directed to interpret this effect in terms of cavitation. While applying the cavitation theory due consideration of the theoretical criteria for inducing cavitation in water by elastic waves have not been taken into account. Therefore, it will be worthwhile to introduce in brief a theoretical discussion on the onset of cavitation in supercooled water and ice by introducing the accepted concept of cavitation.

THEORETICAL CONSIDERATION

The presence of sound waves within a fluid medium implies that the pressure is fluctuating alternately greater and less than an average pressure. The reduction of pressure can reach a value so low that it is below the vapour pressure of the liquid. Under these circumstances, and if the reduction persists long enough, bubbles of vapour will be formed within the fluid itself. This process is known as cavitation.

Theoretically the formation of a bubble of visible size involves two critical steps. The first is related to the formation of the smallest bubble or nucleus which can grow spontaneously as a result of evaporation of the fluid; the second is related to the growth of this nucleus to a microscopic bubble. Cavitation nuclei are vaporous bubbles having a radius larger than the critical one, as a consequence of energy concentration in a small region i.e., thermal spikes, which, subsequently explode. When a thermal spike explodes into a nucleus, effects due to inertia, viscosity, and thermal conductivity of the liquid, come into play and they are difficult to be evaluated exactly. By considering the energy balance for the bubble formation, however, an approximate description of the process may be obtained. Lieberman and Rudnick (1962) treated the case in which a sound wave is present, delivering energy for the cavity formation during the negative part of the pressure cycles.

Messino *et al* (1963) has recently put forward the following mechanism for the onset of cavitation in liquid.

When a liquid in which pre-existing (assumption) nuclei are present is introduced into a sound field, cavitation will appear as soon as a nucleus finds intself in a region where the sound pressure is sufficient for its growth. Nuclei of different radii require sound fields of different pressure. Also within the sound field itself pressure gradient may exist within a small region. The cavitation threshold is to be considered as weighted average of pressures experimentally found in a series of measurements determining threshold of cavitation.

Further, while cavitation may cause nucleation, in some cases it appears unlikely to the author that cavitation will occur in the liquid water droplot of atmospheric clouds. In order for this phenomenon to take place it is necessary that the pressure within some portion of the liquid become sufficiently low that a bubble of vapor can form and therefore in the case of shock waves it requires that the shock wave reduce the pressure in supercooled cloud drops to some value below the vapor pressure of the liquid water. Water at a temperature of 0°C has a vapor pressure of the order of 6 mb absolute and for reasons to be discussed below it seems unlikely that pressure of this order are produced either in laboratory experiment or in a thunderclap. In view of these considerations, the probability of onset of cavitation in hailstone assuming pre-existing water content whose temperature is equal to or less than 0°C, also seems unlikely.

The collapse of a cavitation bubble may produce these effects by generating a high intensity shock wave of the order (200-500) atmospheres. So the mechanisms of the triggering of freezing of super-cooled water and softening of hailstones and ice by shock waves should be sought in a process other than the onset of cavitation.

What effect then can a shock wave produce during interaction with supercooled water ? Shock waves may trigger nucleation by accelerating the particles of water to juxtapose themselves for assuming the ice structure within the effective period of the shock. This idea may be made clear from following considerations. The process of supercooling can be understood if one considers the two steps in the process of crystallization (1) first nuclei must form, and (2) then these nuclei must grow. Depending upon temperature and pressure either of these steps may determine the rate of crystallization. A free energy barrier to crystallization exists, due to the fact that the melting point of very small crystals is lower than that of large one. Thus, in a supercooled liquid, crystals act as nuclei smaller than a certain size have a lower energy barrier. To form a stable nucleus one must first form nuclei having a higher free energy than that of surrounding liquid. The free energy barrier to crystal growth is simply that which prevents the motion of a molecule from one lattice site to another and is therefore, similar to viscous flow. Thus, as the viscosity in a liuid increases, the rate of growth of nuclei decreases but as the temperature of a liquid is lowered, the number of nuclei rises to a maximum. However, at low temperature the rate of crystal growth diminishes, becausee of the effect of increasing viscosity is greater. When the latter effect is predominent, temperature well below the melting point can be reached. In this case, one may reach the so-called glassy state. Further, as the temperature or pressure of a liquid is changed, the degree of order changes. Not only the range of order increases upon lowering the temperature, but the lattice defects decrease. Thus at every pressure and temperature, a degree of order which describes the geometric state is associated with a liquid.

EXPERIMENTS

The following experiments have been carried out to add more informative data. Determination of shock parameters involve sophisticated experimental techniques, so to ascertain the amount of energy and the duration of interaction time required to produce civitation in supercooled water and ice, ultrasonic techniques, whose parameters can be accurately determined, were employed. In these investigations the feasibility of the induction of cavitation by low intensity shock waves in hailstones and super-cooled water has been examined separately

(1) Ice was formed on the metallic electrode of the ultrasonic transducer by placing it in a large thermally insulated double jacketed tank containing water. The tank had windows for shining the ice sample with a collimated beam of light and also windows for visualizing and photographing the ice sample at right angles to the light beam. The transducer was excited at a frequency of 25 kcs at the optimum power level of the amplifier. The maximum ultrasonic intensity was 16 W/cm^2. This corresponds to peak pressure amplitude of about 7 atms i.e. peak inverse pressure of 14 atmospheres. At this frequency and with this power, no effect was observed inside the ice during the first 2 minutes of excitation. As the time of excitation was increased, ice started melting from the surface of the transducer in the axial direction. After 10 minutes of clean hole having the diameter approximately of the ultrasonic beam was made in the ice. No. weakening outside the boundary of hole was noticed. Chronological stages were studied photographically. Since with this high intensity ultrasonic wave interacting for 2 minutes cavitation in ice could not be produced, therefore from this result it is most unlikely that shock intensity of the order of a fraction of 1 atm interacting for a few milliseconds (2 ms) would induce cavitation in ice. Further 2 minutes treatment with this intense ultrasonic wave did not show any weakening of ice. Experiments were repeated with 10 such samples.

(2) Natural hailstones contained in a nylon net, were suspended at a distance of 6 inches from a 1 ft. long weather cord explosive held vertically. After explosion, some of the samples were found broken at protruded portions. In order to check that this was due to the effect of the direct impact of explosive

one isolated hailstone at a time was subjected to the similar explosive shock-wave. No breaking and no weakening of the hailstones were observed. The breaking in the former case was due to the mutual impact of the hailstones. Shock waves set up translational motion of the hailstones, thereby causing mutual impact. In the case of a freely suspended target hailstone the portion of incident energy that will be expended in producing deformation will depend upon the viscous drag of the medium in which the target is suspended. If the medium is air, the major portion of the impulse acting on the target will be transformed into translational energy of the target. Possible observable effects would be located on the surface only. In the case of atmospheric hailstones, weakening would be possible, only when there are collisions.

(3) Experiments have been carried out to produce acoustically induced cavitation in water contained in 3 litre pyrex glass sphere. In principle the experimental techniques were similar to those used by Galloway (1953) and Lieberman (1958). In this experiment, the sphere was surrounded by two concentric stainless steel hemisphere in order to cool the water down to about (3-5°C.) The sphere was excited in radial mode of vibrations. The threshold of cavitation was measured by PZT4 pre-calibrated transducer. At room temperature, the threshold for cavitation in degassed distilled was measured 23.5 atm (max), but at the temperature range (3-5°)C, the maximum pressure developed at the center of the sphere was 72 atmosphere but there was no onset of cavitation. Due to the technical difficulty of the power amplifier, more power could not be fed into the transducer to observe the onset of cavitation. This result indicates clearly, however, that the magnitude of pressure required for the onset of cavitation is more than 72 atmosphere. Lowering the temperature and shielding the resonating sphere much higher values of the threshold for cavitation were obtained consistantly in this experiment. The details of this experiment will be published elsewhere.

CONCLUSION

Laboratory experiments show definitely that ultrasonic energy of 16 watts/cm^2 could not produce cavitation either in ice formed on the transducer itself nor in degassed water cooled to (3-5°)C. Therefore shock overpressure of a fraction of 1 atm lasting for about 2 millisecond is not intense enough to induce cavitation in hailstones or in supercooled water.

However, the phase transformation of supercooled water to ice by shock wave is an experimental fact. The fundamental reason for the appearance of nuclei in a homogeneous substance is the existence of fluctuations (i.e. transient local deviations from the normal state). The deviations can occur in any part of the substance as fluctuations of local energy or density. These fluctuations occur at all times, but only under certain conditions can they become large enough to produce and nucleate phase transformation. Shock wave increases the rate of fluctuations.

Following mechanism is suggested as the cause of phase transformations by shock waves. Since the water molecule is dipolar, the triggering of freezing of supercooled water is due to the translation and rotation of the dipole. In the supercooled state, which is highly viscous, molecular diapoles, inspite of their metastable condition, are incapable of orientation and translation to assume the ice structure because of the energy barrier created by the higher viscosity of the medium medium. Energy supplied from external source such as shock wave, ultrasonic wave, chemicals, mechanical agitation, enable the molecules to circumvent the energy barrier. Goyer (1965) in a recent review article has suggested the onset of cavitation as a probable mechanism for the triggering of nucleation in supercooled water by the impact of 1.1 psi shock over pressure lasting for about 2 ms. The theoretical reasonings and the experimental results presented here are not compatible with Goyers idea. Further Goyer and Favreau (1965) claim a 30% decrease in strength of the ice structure due to the impact of low intensity-shock wave. Experiments presented here indicate however that there is no detectable reduction in the strength of the ice.

Bhadra (1968) carried out a series of experiments to show the effect of air content on the freezing of water and to demonstrate that the dynamics of air bubbles can trigger freezing of supercooled water. These air bubbles released from the mass of the liquid should not be confused with cavity bubbles. Air bubbles growing in the mass of the liquid due to the interaction with physical disturbances, move to the surface and vanish in the atmosphere. Whereas the cavity bubbles during growth and collapse processes develop high pressure in the liquid. This pressure acts in a way similar to that by shock waves; the mechanism of the interaction has already been described. Low intensity ultrasonic waves and shock waves are capable of releasing the air absorbed in the liquid. The dynamics of these air bubbles in turn can trigger freezing of supercooled water. So for the reasons given above, the phenomenon of cavitation is not necessary to explain freezing of water but it is simply a matter of supplying sufficient energy to the supercooled system so that the H_2O molecules will reorient themselves in the ice structure.

Further investigations to pin point the mechanism of the freezing of supercooled water and weakening of ice by low intensity shock waves are under progress.

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